An Assumption of R&D Method Driven by Model and Data

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Abstract. The model-based systems engineering is gradually applied to the development of complex systems, it has the advantages of accurate transmission of design output, rapid response to design changes, and undemanding reuse of design achievements. In this paper, MBSE is evaluated from three perspectives, including the theoretical system of model-driven research and development (R&D), the requirements of product R&D as well as the requirements of complex system R&D, and the shortcomings of MBSE are sorted out. On this basis, this paper proposes the R&D process of complex system hybrid-driven by model and data, and analyzes the key technologies to be solved.

Keywords: Digital Prototype · Metamodel · MBSE · Systems Engineering

1 Introduction

Complex systems, especially oriented towards high-security, have high risks in terms of technology, quality, schedule, cost and management in the design, production, use and maintenance throughout the whole lifecycle [1, 2]. Against these backdrops, model-Based Systems Engineering (MBSE) methods are increasingly used with the development of complex systems, which has the advantages of accurate transmission of design output, rapid response to design changes, and easy reuse of design achievements [3]. At present, there are modeling and analysis tools at various levels, such as hierarchy, system, software, hardware, and device, which support process-based design, quantitative analysis, digital simulation, virtualization integration, formal verification, digital production and other methods. Functionally, it can effectively improve the quality and efficiency of design, production and maintenance, by reducing costs and securing risk control. In addition, the advanced development of artificial intelligence and big data technology as well as its in-depth application in the commercial domain have promoted the transformation of complex system from “digital design” to “intelligent design” where data and intelligence serve as the core.

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2 Product Development Process: An Analysis

Systems engineering is a way and method to enable the system to achieve the expected goals successfully, forming a structured development process from conceptualization to production and then to operation. The fundamental rationale of systems engineering lies in providing high-quality products that meet the needs of users, while catering to the business and technical constraints of customers, developers, and suppliers. Besides, systems engineering also focuses on the product development cycle where customer needs are defined and documented at an early stage [4], then designed and implemented, and finally undergoes synthetization and validation. In this process, comprehensive and careful consideration is fully given to technology and implementation, performance and benefit, production and supply, cost and schedule, operation and use, training and support, exit and destruction, and other issues in the whole lifecycle.

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a) The R&D system refers to the R&D mainly involved in the whole product lifecycle, such as system engineering, electronic engineering, software engineering, test engineering, manufacturing, product inspection, and customer service. It is a collection of all the processes involved above along the temporal veins of product R&D;
b) Domain technology system refers to the professional domain mainly involved in product R&D. Taking the display & control system as an example, it includes the overall system design, graphics generation, ergonomics and other professional directions, which is the knowledge set of product-oriented technology dimension.
c) Project management system refers to the management process mainly involved in product development, including the management of cost, quality, schedule, resource, communication, risk, procurement, related party and so on, which is the management set of enabling dimensions of product R&D.

With the gradual upgrading of industrialization level and the continuous improvement of product lifecycle-managing requirements, a series of methodologies and guidance manuals have been formed to meet the professional and scientific expectations of R&D system and project management system, among which a typical one is INCOSE's Systems engineering Manual [5]. In order to cope with the exponential increase in the complexity of industrial products, a series of methodology oriented to the R&D system has been formed, with MBSE as the most typical one.

3 Model-Based Systems Engineering

3.1 MBSE Reevaluation

Assessment From The Theoretical System of R&D Model Driven. Putting aside the logical constraints of the MBSE methodology [6] defined by the Harmony SE methodology, from the perspective of logical analysis, the modeling of MBSE is similar to that in mathematics and physics. By constructing a set of theoretical system/methodology, the nonlinear physical world is deconstructed into a linear physical model/data model, where the uncertainty is controlled so as to predict and intervene in the real world. A complete modeling system is usually followed, including:

a) Model language provides a method to deconstruct nonlinear realistic products into linear expression in a certain dimension, which can be a geometric (size, shape, assembly), functional, or physical (heat, force, material), etc.;
b) Modeling tools contribute to a tool environment that supports the transformation of product linearizing models into simulation models that can be implemented by computers.

MBSE is a system that introduces "modeling" into the systems engineering and uses formal models as the main design carrier during product development. Typical MBSE methodologies include Harmony SE by IBM, MagicGrid by No Magic (later acquired by Dassault), and Arcadia by Thales. The final component in model-based design is the digital twin, which realizes the data fusion of all elements, full business, multi-dimensional, multi-scale, multi-domain, and multi-disciplinary models, and supports the operation simulation of the whole lifecycle.

Analysis From the Perspective of Product R&D Requirements. Product digitalization refers to the digital expression of product entities, management activities, and external space [7] with reference to the complex system, rapid evolution, and environmental interaction of complex system construction, which further builds a digital model system centered on the operating systems, product requirements, digital prototypes, digital products, and evaluation models [8–12]. In the digital space, product lifecycle construction and management activities [13, 14] such as top-level planning, product demonstration, development and production, test validation operation guarantee are carried out to establish a new paradigm of product development with virtual and real interaction and to solve the problem of lagging product development and operation management models. The focus will be loaded on the following issues: digitalization of product entities, management activities, and external spaces. Among others, the digital model elements are defined as follows (Tables 1 and 2) (Fig. 1):

Table 1. Product digital model elements composition table.

Model name	Model element composition	Function realization	Application stage
Operation System Model	Driven by application requirement, including system application scenario, system collaboration, product capability demand, etc	Support system simulation deduction, realize system design optimization, promote operation concept innovation	Top-level planning

(*continued*)

Table 1. (*continued*)

Model name	Model element composition	Function realization	Application stage
Product Demand Model	Based on the operation system involving product application scenarios, collaborative relationships, capacity requirements, etc., it specifically includes mission tasks, system positioning, operation scenarios, application indicators, test requirements, "six characteristics" requirements and other elements	Support product demonstration multi-scheme optimization, to achieve accurate generation of product demand	Product demonstration, development and production
Digital Prototype Model 1.0-design	Based on the product demand model, it includes system architecture, structural layout, internal and external interfaces, functional performance, physical characteristics (mechanical, electrical, hydraulic, thermal, magnetic), universal quality characteristics etc	Support rapid design of system solutions, virtual simulation, and iterative optimization of solutions	Development and production
Digital Prototype Model 2.0- manufacture	On the basis of digital prototype model (1.0-design), model elements such as process parameters, material properties, manufacturing means, processing accuracy and product procedures are added	Support product virtual processing, virtual assembly and virtual-real combination of testing and verification, to achieve high-quality, low-cost manufacture	Development and production
Digital Prototype Model 3.0- delivery	On the basis of digital prototype model (2.0-manufacture), some details that users do not need are removed, and model elements such as product delivery status, guarantee requirements, application mode, operation process and maintenance characteristics are added	Support virtual real performance test, realize simultaneous delivery of digital prototype and physical prototype, and support test identification	research and manufacture, test identification
digital product model	On the basis of digital prototype model (3.0-delivery), add digital resume elements, collect real-time status information, form digital twins of products	Support system performance test and product performance boundary assessment, and realize situation monitoring, health status management, system operation deduction, support demand calculation, support action planning, and product health management after delivery	Test identification, operation guarantee

From the defined product digital model, it can be seen that the models included are multi-dimensional and multi-level in terms of product lifecycle. Meanwhile, the system of digitalized empowering products must be established on the basis of consistent, continuous and authoritative transmission of models and data to ensure that the efficiency of digitalization construction can be maximized.

Reassessment of R&D Requirements From Complex Systems. The complex system is usually a typical physical entity formed by the integration of multi-physics systems, multi-disciplines, and multi-domains. From the model definition dimension, its digital model at least includes geometry (size, shape, assembly), physics (comprehensive consideration of mechanics, thermology materials, etc.), behavior (precise response based on external input such as the environment and system uncertainty factors), rules (relying on the operation rules of the system to achieve the evaluation and optimization function of the system) and other multi-dimensional spaces. In order to explore the feasibility of MBSE, the models/data clusters of complex systems are classified according to the engineering stages/domains of system development**.**

Table 2. Models/data of complex systems at different stages of R&D.

System R&D Domain	Model/Data
requirement analysis domain	scenario analysis model
	demand data
function design domain	function model
	algorithm model
	man-machine interaction model
architecture design domain	physical resource configuration evaluation data
	functional architecture design model
	Logical interface model
	interface control document
	man-machine interaction model
	reliability model/data
	security model/data
	testability model/data
	maintainability model/data
software design and development domain	software interface model/data
	software data model/data
	man-machine interaction development model/data

(*continued*)

Table 2. (*continued*)

System R&D Domain	Model/Data
hardware design and development domain	electronic engineering model/data
	hardware interface model/data
	electromagnetic characteristics model/data
	structural model
	thermal simulation model
	intensity model
	signal integrity model
	power supply characteristic data
	RF channel model
process design domain	process model/data
	cable laying model
	tooling model/data
integrated verification domain	test case model/data
	simulation model/data
	assembly simulation model
	workshop logistics model

3.2 MBSE Problem Analysis

Based on the summary from the practice, the solution provided by the Harmony SE methodology currently adopted is limited by modeling language and modeling tools, which only supports demand analysis, function design and architecture synthesis, satisfying the requirement model, function model, behavior model, requirement decomposition and function model confirmation in the process of system design. It is still unable to construct multi-dimensional and multi-domain model and conduct co-simulation, and there is still a long way toward digital R&D of product. For the development of complex systems, it has not yet been able to provide a complete solution for various models or data required by products, and due to the relatively closed tool ecology, it is difficult to realize the interaction with other system design and development tools. At present, only a certain dimension or a certain type of model of the system can be expressed linearly, and only the R&D work of system design section can be supported. For the time being, it is not yet possible to achieve multi-dimensional integration and penetration across R&D stages.

Therefore, taking the Harmony SE methodology as a representative and characterization of MBSE is one-sided. It is necessary to conduct a full comparative analysis of various MBSE methodologies, follow up the latest modeling language research results, and explore more effective modeling tools.

Meanwhile, compared with the three elements of the product development process, the current MBSE methodology focuses on the "R&D process system", which does not cover enough domain knowledge, and its completeness and maturity cannot support the product development system to fully tilt towards the MBSE methodology. On the contrary, MBSE should be incorporated into the R&D process system as a solution for the modeling design and validation of the requirements analysis, function design, architecture design and other processes in the "systems engineering process" of the R&D process system.

4 Systems Development of Model & Data Hybrid-Driven

4.1 R&D Process Assumption

In order to carry out complex system product development more effectively, the research and development process in line with the characteristics of complex system domain is built by considering two dimensions of product R&D system and domain knowledge. Drawing on the American digital engineering strategy, a methodology of hybrid driving of complex system models and data is proposed in this paper. The main implementation approaches include:

a) introducing the "metamodel-based" modeling concept. As the model of a model, metamodel is applied to analyze, construct and develop a set of framework, rules, constraints and theories for modeling certain problems. The lowest-level description that forms various modeling languages is the data structure corresponding to the domain knowledge represented by the model. Through the application of metamodel, the following targets can be attained:
1) By fully combining the model-driven design process with the professional system in domain, the professional domain knowledge can be presented through metamodel so as to standardize the knowledge and enhance the quality of system modeling.
2) Through the abstraction of metamodel, a shared database of multidisciplinary modeling can be built to support data transmission across production relations, sustain information traceability from the demand end to the design and test end, and provide feasibility for establishing the main line of the whole life cycle of complex systems.
b) building a single-source digital main line for the full life cycle of complex system products. First, the tool chain of product R&D should be inserted to realize the storage and management of information formed during the R&D process, support the transformation and traceability of models and data formed by various tools, effectively connect the R&D process and transform the process-driven R&D process into a data-driven one. Meanwhile, the data mainline supports the abstraction and encapsulation of models and data into domain knowledge and CBBS, enriching the product platform of complex systems, effectively promoting the full reuse of domain knowledge and CBB results in the R&D process, and improving the quality of product R&D.
c) establishing a set of R&D tool environment that supports the hybrid drive of "model and data". Instead of adhering to the full-dimensional and whole-process model-driven design pursued by fundamentalist MBSE, this environment considers the R&D requirements of complex systems realistically, and take decoupling (among tools),

redundancy and specialization as the criteria. Specifically, the system design process, software design and development process, hardware design and development process, system testing and verification process are decoupled. The professional differences of each design process are fully considered and the model-driven design is priorized to be the implementation scheme. For those design process that cannot be presented through model, various "digital" design methods are fully applied and theoretical analysis, model simulation, knowledge reuse can also be applied. Each R&D process is effectively connected through the digital main line to promote multidisciplinary collaborative design, and support the reuse of knowledge and CBB.

d) Continuously optimize and enrich the R&D system of complex systems, undertake model and data hybrid driving theory, combine tool environment support, apply the main line of life cycle data, and realize effective collaboration in the R&D process. Incorporate the complex system technology system into the methodology, supplement and improve the process definitions and method descriptions such as human-computer interaction design and evaluation, architecture design and evaluation, OODA algorithm design and simulation, and physical architecture trade-offs.

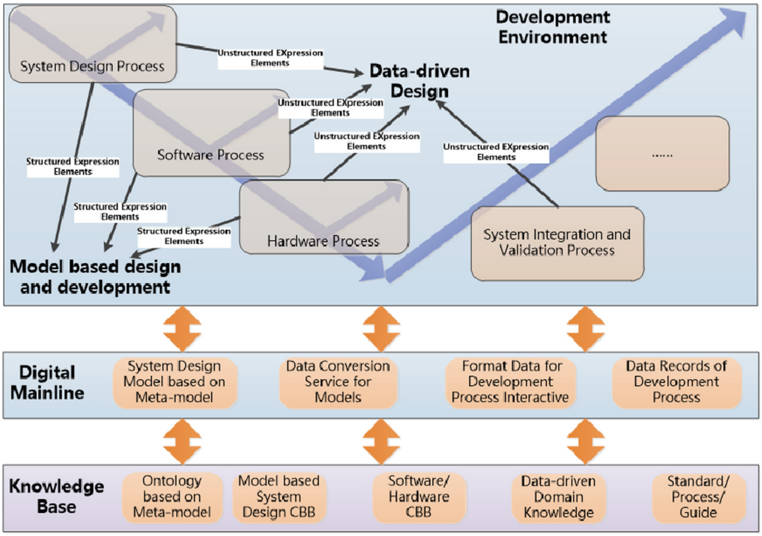

Fig. 1. Development Schema Driven by Model and Data.

In the end, the digital development ecosystem is to be developed, which is based on the system engineering of the research and development, the core of model data line, and the development of the tool environment, improves the efficiency of the development of the avionics system and the quality of the product.

4.2 Key Technology

Full Digital Prototype Modeling Method Based on Domain Ontology. Combined with the system design process, the construction methods of functional prototype, performance prototype and geometric prototype involved in the design and development of complex systems are studied, and the design information transfer interface specifications between prototypes are standardized. The functional prototype is built to digitally model the system requirements, structure, behavior, and parameter functions involved in the development of the airborne system; The geometric prototype is built to visually design, analyze and verify the physical and geometric characteristics of prototype system products and related features such as heat, strength and Electro Magnetic Compatibility (EMC). The performance prototype is built to conduct AADL-based physical architecture modeling evaluation and virtual integration for complex systems and subsystems [14] and build a math-based performance analysis model on the basis of collaboration with the functional prototype, in order to support the definition, analysis, evaluation and optimization of complex system performance indicators such as performance (MOE), effectiveness (MOP), timing, MTBF and cost. Through the definition of domain ontology, a unified basic description of the model, data organization and knowledge in the full digital prototype analysis technology system is presented.

Multi-domain Heterogeneous Model Co-simulation Optimization. The digital design of complex systems involves models in various disciplines, such as machinery, electronics, control, etc. Different disciplines rely on different modeling tools. In order to realize the simulation of full digital prototype, it is necessary to study the co-simulation technology of heterogeneous models in multiple domains. From the longitudinal dimension, the model-driven mechanism of airborne system design in different design stages needs to be explored, and construct a standardized design information exchange method based on XML. From the horizontal dimension, the co-simulation mechanism and model encapsulation method of geometric prototype, functional prototype and performance prototype requires to be studied. Study on multidisciplinary collaborative optimization technology, comprehensive evaluation and analysis of complex system design architecture characteristics, performance indicators, functional requirements, structural characteristics, etc., should be conducted to ensure that airborne systems meet mission and task requirements.

Interdisciplinary Tool Software Collaborative Design Environment. An all-digital MBSE standardized process should be established to achieve accurate management, lossless transmission, instant processing and rapid feedback; in addition, it is also conducive to adapt to demand adjustment, rapidly respond to business emergencies, and timely manage and control business exceptions. In the collaborative tool chain environment, there are not only commercial system design tool software, but also self-developed design tools. At different stages of product and system development, design results can be inter connected and utilized across different tools. The collaborative platform adopts the model-based development method and takes the model as the center to integrate design tools such as requirements, functions, architecture, ICD, POP, DD, simulation, airborne software, airborne hardware and integration test in the process of R&D, so as to realize the refined inheritance design and traceability verification of the model.

Model Data Management Based on Single Data Source. Collaborative data management is the basic capability of the avionics design collaborative platform. It stores and manages various types of data generated in the design, analysis, test and quality during the product development process, including 3D models, 2D drawings, technical documents, standard specifications, and will realize the integration with electronics, structure, simulation, process and other tools, build a single design data source to ensure the consistency, validity, integrity, traceability and security of transmission. At the same time, a data center with the project as the management object is established, for the global data generated in the development process and the coordination data between different design companies, to realize the storage, summary and release management as well as backup and query and other functions of controlled data under a unified technical state. Through the cleaning, grasping, integration, statistics and analysis of various master data in the whole life cycle, the system architecture integration and data management platform can carry out mining and sorting of the big data of enterprises in real time, and provide intelligent analysis value-added services for business decisions.

5 Conclusion

In this paper, MBSE is evaluated from three perspectives: theoretical system of model-driven R&D, requirements of product R&D, and requirements of complex system R&D. MBSE is still unable to provide a complete solution for various models or data required by products. Currently, it only supports the linear expression of a certain dimension or a certain type of models of the system, and only supports the R&D of the system design section, but is still unable to achieve multi-dimensional integration and implemented throughout each R&D stage. On this basis, this paper proposes a complex system R&D process hybrid-driven by models and data, analyzes four key technologies, including digital prototype modeling method, heterogeneous model co-simulation optimization, collaborative modeling environment and collaborative data management.

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